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Figure-of-Merit Definitions for the Stationary/Slow-Moving and Air Vehicle Target Detection Algorithm Performance Study

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This report defines the figures-of-merit (FOMs) agreed upon by Task Group II of the Technical Coordination Program (TTCP) Joint Advisory Group (JAG) 12 data processing workshops held at NAVOCEANSYSCEN, San Diego on 25-30 March 1985. These FOMs can be applied to stationary, slow- and fast moving target detection algorithm performance assessments.

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1.0 INTRODUCTION

The increasing sophistication of optical component and detector technology, coupled with rapidly expanding surveillance requirements, suggest that multispectral infrared sensor systems may soon provide additional capability to the member nations of The Technical Coordination Program (TTCP) for strategic defense and intelligence gathering applications. The Defense Advanced Research Projects Agency (DARPA) has been pursuing the extension of the Department of Defense surveillance capabilities during the past several years through the Hi-resolution Calibrated Airborne Measurements (HI-CAMP) and TEAL RUBY programs. Specific tasks within these efforts include infrared (IR) detector technology development, background clutter statistics and target signature measurements, IR phenomenology, and digital signal processing. Results of these efforts are being archived for future study and use at the Environmental Research Institute of Michigan (ERIM).

To evaluate the near-term potential of this technology in the aforementioned roles, member nations of the TTCP are conducting a number of joint HI-CAMP and TEAL RUBY experiments in each of their respective countries. An intent of the effort is for all members to share their data analysis techniques and results. These analyses take advantage of all the TEAL RUBY data analysis work performed to date, but have been recently broadened to include a detection algorithm evaluation as well. Key to this technology evaluation is the use of common computer algorithms, characterization parameters, and performance assessment figures-of-merit (FOMs) in the data analysis portions of each experiment. This will insure that the information and conclusions drawn from this work can be discussed among the various TTCP researchers without definitional misunderstanding or ambiguities. References 1 through 3 outline the results of the TTCP Joint Advisory Group (JAG) 12 Data Processing Workshop held at the Naval Ocean Systems Center (NOSC) during the week of 25 March 1985. The workshop established a common set of algorithms, characterization parameters and figures-of-merit (FOMs). The reports are fairly complete and require only the mathematical definitions of the figures-of-merit before distribution to the general TEAL RUBY community for implementation. This report will provide the specific definitions of the FOMs agreed upon in reference 2. This information is required for the USER-COMMON target detection algorithm performance assessment defined in reference 4, as well as for future HI-CAMP and TEAL RUBY target detection analyses. Future discussions and recommendations concerning the contents of this document can be made either to the author or to the chairman of the TTCP/TEAL RUBY Target Detection Algorithm Group (Task Group II), Dr. Albert LaFlamme, Defence Research Establishment Valcartier (DREV), Courcelette, Quebec, Canada.

2.0 BACKGROUND

References 5 through 10 provide excellent reviews of current image-processing trends and illustrate their utility for enhancing the inherent information found in remotely sensed multispectral imagery such as that taken by the LANDSAT and NIMBUS-7 satellites. At present, the most pressing problem in infrared surveillance is that of under-resolved, weak target detection in highly spatially structured optical imagery. The accepted approach for extracting targets in this case is to temporally bandpass that data through either an analog or digital filter, e.g., frame-to-frame subtraction or a third-order transversal filter (references 11 and 12). This technique is known to produce excellent results if the target is moving or if there is a time-varying feature in the target signature. However, if the object of interest is stationary or slowly moving, other means must be employed to identify and localize the target. Task Group II of the TTCP/JAG-12 TEAL RUBY Panel was asked to address this signal processing issue during the data processing workshop cited above. Their conclusions and recommendations are given in reference 2, and will be outlined in the following subsections.

2.1 BASIC HI-CAMP/TEAL RUBY DATA PROCESSING PROCEDURES

Figure 1 illustrates the basic data processing procedures one can use in analyzing TEAL RUBY- and HI-CAMP-derived data. The first processing module registers sequential frames by eliminating frame-to-frame drift, jitter, and geometrical distortions. Multispectral processing is then applied to the registered imagery, followed by spatial and temporal filtering. The spectral processing requires the true infrared (IR) irradiance values, so it must precede the spatial and temporal filtering algorithms. The specific forms of the temporal filters are somewhat target- and background-dependent, and therefore must be defined beforehand, in the form of filter banks, to assure target detection in the absence of a priori vehicle information. However, the combined intent of these three processing modules is to reduce variance of the background clutter and system noise with minimal impact on the target's perceived intensity structure.

The resulting filtered imagery is then thresholded in both a positive and negative sense to yield a binary map of intensity exceedances as a function of several threshold levels. As the threshold level is increased, it is expected that false exceedances will disappear and only the true target location will ultimately remain. However, null detections can occur in this situation if the local signal-to-noise ratio (local apparent contrast divided by the standard deviation of the image noise) is not strong enough. If the target is slowly moving, several time-separated processed frames can be brought together to form a track of intensity exceedances demonstrating linear or curved motion.

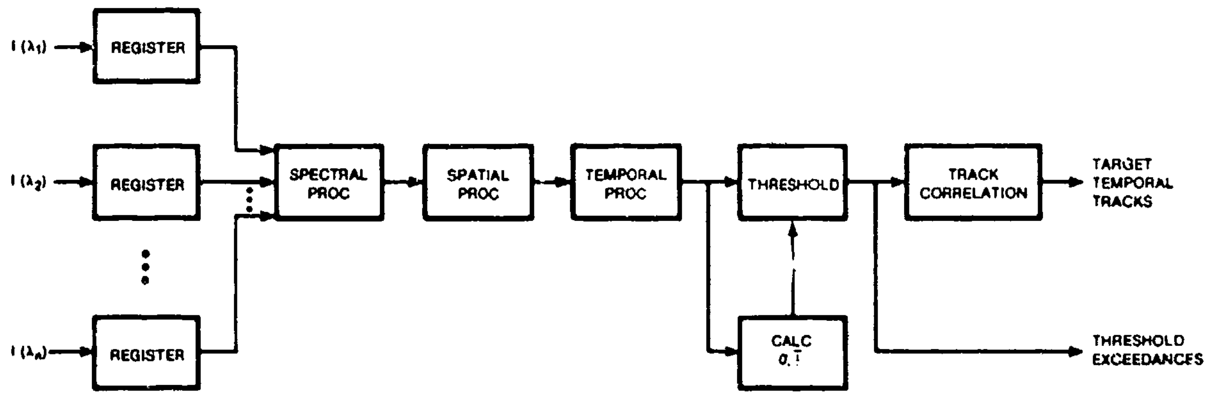

Figure 1. Basic data processing concept showing the individual processing modules.

2.2 TASK GROUP II'S RECOMMENDED APPROACH

Given the current set of TEAL RUBY experiments proposed by the member nations of the TTCP, there appears to be sufficient margin in almost every test to insure reasonable target detections without the need for multispectral processing of the calibrated IR image sequences. Task Group II recommended its omission from the USER-COMMON set of proposed image processing procedures and any experiment requiring its use be treated as a USER SPECIFIC analysis. On that basis, the recommended USER-COMMON data processing procedures for all TTCP TEAL RUBY experiments is to input the calibrated IR scenes at the spatial processing stage of figure 1 and to continue on from that point to the end. It is assumed that these image sequences have been registered using any of the jitter suppression algorithms presently available in the USER-COMMON image-processing algorithm suite. See references 13 through 16 for detailed descriptions on the two techniques implemented at this time.

The prospective set of TTCP TEAL RUBY experiments also indicates that most planned targets will be either of an unresolved, limited spatial extent, or point-like. This reduces the number of potential spatial filter choices to eight generic types. Table 1 lists the current suggested set of spatial filters

Table 1. Suggested set of spatial filters.

1	3x3 point target filter
2	5x5- and 9x9-element Wiener filter
3	Sobel edge detector
4	3x3 Laplacian filter
5	3x3 low pass smoothing filters
6	3x3 and 5x5 Laplacian submedian filters
7	5x5 double-gated detection filter
8	BLOB filter

These filters are described in reference 2. hence. will not be discussed here. The potential performance of these filters in localizing targets in IR imagery have been assessed by L. Sevingny of DREV (reference 17) and also by E. Winter of Technical Research Associates (reference 18). and are available to the interested reader upon request.

The resulting set of images emerging from the spatial filter module will either be simply thresholded or track correlated at his stage of the processing train. In the former case. each filtered image will be bipolar-clipped to form two resulting binary scenes. The first will have each output intensity above a certain level set to one and the rest set to zero. The second will have each output intensity below a certain level set to minus one and the excess set to zero. These thresholding procedures will be evaluated at the three specific levels. as described in a later section. and will be stored for subsequent analysis. In the latter case. a number of thresholded frames are evaluated in terms of adjacent exceedances within a 3 x 3 window. and these results are also stored for later analysis. A more detailed description of track correlation can also be found later in this document

3.0 FIGURES-OF-MERIT DEFINITIONS FOR TARGET DETECTION CHARACTERIZATION

To compare the performance of the various processing techniques in localizing potential targets and/or tracks in HI-CAMP and TEAL RUBY IR imagery, a common standard of assessment must be employed. Table 2 gives the recommended sets of FOMs for general performance comparison. All but items 6 and 7 can be applied to arbitrary target detection and position localization. These last two items are limited to the moving target detection assessments only. We will give detailed descriptions of these figures-of-merit in this section.

Table 2. Recommended sets of FOMs.

1	Background noise suppression parameter
2	Mean target contrast
3	Mean target signal-to-noise ratio
4	Threshold exceedance maps
5	False alarm rates
6	Track correlation
7	Track quality parameter

3.1 BACKGROUND NOISE SUPPRESSION PARAMETER

The goal of any target detection algorithm is to enhance the presence of signals of interest by suppressing background clutter and noise. This is usually achieved through the use of some sort of linear filter being applied to image or image sequence that is optimally designed for the potential targets and background contained therein. An important characterization parameter in assessing the degree of clutter/noise reduction achieved by this filtering action is the background suppression FOM given by

$$\beta = \frac{\text{Noise variance before processing}}{\text{Noise variance after processing}} \tag{1}$$

The larger this parameter, the more clutter/noise reduction occurred. If β is less than one, we have actually degraded the image. A value of one implies a zero difference in reducing the clutter/noise after processing. The mathematical definition for the variance of image clutter/noise is

$$\overline{B^2} = \frac{1}{47} \sum_{i,j=-3}^{3} [x(m+i,\ n+j) - \bar{B}]^2 \tag{2}$$

$[(i,j) = (0,0)$ excluded$]$

for a point target located at pixel (m.n). and

$$\overline{B^2} = \frac{1}{59} \sum_{i,j=-4}^{3} [x(m+i,\ n+j) - \bar{B}]^2 \tag{3}$$

$[(i,j) = (0,0),\ (-1,0),\ (0,-1),\ (-1,-1)$ excluded$]$

for a four-pixel extended target. The calculation windows for these definitions are given in figures 2a and 2b respectively. The normalization factors of 47 and 59 found in the above two equations. respectively. are computed by subtracting the number of target pixels from the unbiased normalizing factor (n-1). n being the total number of pixels within the processing window. Also in the above equation. B represents the mean background noise level and is calculated using the same windows as defined for the variance given previously. Specifically. we have

$$\bar{B} = \frac{1}{48} \sum_{i,j=-3}^{+3} x(m+i,\ n+j) \tag{4}$$

$[(i,j) = (0,0),$ excluded$]$

for a point target and

$$\bar{B} = \frac{1}{60} \sum_{i,j=-4}^{+3} x(m+i,\ n+j) \tag{5}$$

$[(i,j) = (0,0),\ (-1,0),\ (0,-1),\ (-1,-1)$ excluded$]$

for a four pixel extended target

Unsymmetric or other target shapes not covered by these definitions can have the local suppression of image noise assessed by completely encompassing the target with either a rectangle or square (whichever possesses the smallest. but best fit) and using a four-pixel-width annulus as the calculation window An example window is given in figure 3 The mean and noise variance calculations are performed over those pixels within the window. but not contained in the target window The mean level is

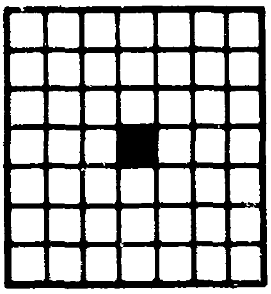

Figure 2a. Single pixel target processing window.

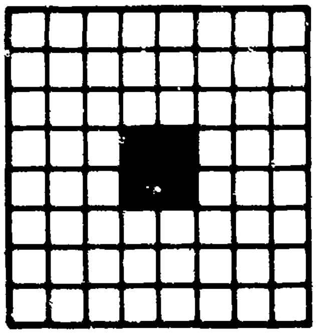

Figure 2b. Four pixel extended target processing window.

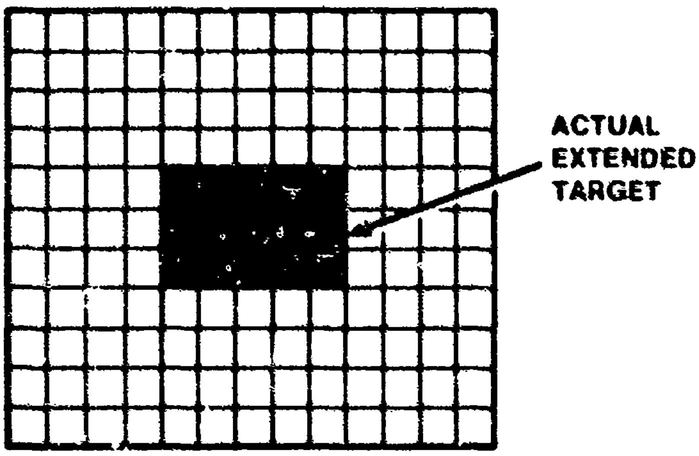

Figure 3. Example processing window for an arbitrary extended target shape

normalized by the total number of pixels with the annulus, and the noise variance by that value minus one. All of the above mathematical definitions describe the local processing gain relative to a target's location. For a more global assessment of noise suppression, we can compute the image clutter variance over the entire image, minus a five-pixel border surrounding the frame of interest, when no targets are present.

3.2 LOCAL TARGET MEASURES OF PERFORMANCE

If we destroy target intensity while suppressing image noise and clutter, the goal of target detection is lost even though significant noise suppression may be achieved. Hence, we have to apply processing techniques that will reduce image noise, yet minimally degrade the perceived target shape or intensity level. This implies that additional FOMs besides the above are needed to truly assess target detectability. The most common figures in evaluating this facet are the apparent mean target contrast and the mean target signal-to-noise ratio (SNR). A proposed set of definitions for these two performance measures is given in the following two subsections.

3.2.1 Apparent Mean Target Contrast.

The apparent contrast of any target within a particular scene is just the relative difference of its intensity and the local mean background clutter level. Unfortunately, the fact that we are generally dealing with under-resolved imagery suggests that a clear assessment of target signature from this data is unachievable for most proposed targets of interest. For example, an F-4 will comprise only some fraction of a TEAL RUBY footprint and background scene radiance will contribute the rest of the received intensity recorded there. If the combined background level is very small compared to the F-4 signature, we can assume the perceived energy is mostly target. If this condition is not true, we cannot get a clear-cut assessment of target level. This impacts model comparisons and implies that great care must be taken in comparing experimental data with theoretical predictions. However, in terms of target detectability, this is a fact of IR surveillance and we can apply the standard definitions recognizing that all processing techniques must contend with background/target averaging. The signal intensity level is computed by averaging the intensity levels associated with the assumed target shape, e.g., point target, four-pixel extended target, etc. Given this computed value and the mean noise level defined above, the mean target contrast can be evaluated using the relation

$$C = \frac{\bar{S} - \bar{B}}{\bar{B}} \qquad (6)$$

3.2.2 Mean Target Signal-to-Noise Ratio.

The mean target SNR is defined as the ratio of the apparent contrast divided by the standard deviation of the clutter normalized to the mean background level. Mathematically we have

$$SNR = C/\sigma \qquad (7)$$

where

$$\sigma = \sqrt{\overline{B^2} \,/\, \overline{B}^2} \quad (8)$$

is the normalized standard deviation of the noise/clutter. It is apparent from this l. .t equation that SNR denotes a voltage SNR and must be squared if the power SNR is desired. We recommend specifying SNR in decibels (dB) so no ambiguity can occur (recall that quantities in dB always reference to power).

3.3 THRESHOLD EXCEEDANCE MAPS AND THEIR ANCILLARY PRODUCTS

In the previous sections we addressed a set of deterministic measures of detection algorithm performance. However, target detection is basically a statistical process and therefore the above FOMs need to be augmented with assessment parameters which take this aspect into account. In this section we will define a set of performance measures that will fulfill this requirement

3.3.1 Intensity Thresholding.

For each output image produced, a first order target detection assessment can be achieved by thresholding each image at various specified levels to yield binary maps of potential target locations. Because of the positive/negative contrast possibilities inherent in most calibrated HI-CAMP/TEAL RUBY images and their clear existence in frame-to-frame difference data, bipolar thresholding should be performed on all processed image sequences (except in the case of Sobel filtered images where the resultant output is set to positive real and integer values relative to a zero background level) The threshold level equations suggested by Task Group II are

$$TH(+)=\bar{B} \cdot (1+a \cdot \sigma) \text{ and } TH(-)=\bar{B} \cdot (1-a \cdot \sigma) \quad (9)$$

where

$$a = 2,\ 4,\ \text{and } 6$$

and the other parameters were defined previously These binary maps will then be stored as analysis products and will be used to compute the information described in the next two subsections

3.3.2 False Alarm Rates.

Using the binary maps derived from intensity thresholding the threshold exceedances can be summed and normalized to the total target areas within a set of image sequences to yield first order probabilities of false alarms (false alarm rates)

These numbers can be plotted and stored as an ancillary analysis produced with the threshold exceedance maps. These graphs can be derived from either moving or stationary IR image sequences.

3.3.3 Track Correlation.

In a first order attempt to reduce false target occurrence in HI-CAMP/TEAL RUBY moving target data runs, a track correlation algorithm will be applied to these image sequences. Specifically, a 3 x 3-pixel window function will be used on each fixed-threshold binary map sequence of length M. The target location (or track) is declared valid if N or more exceedances are counted with the window in M frames. Task Group II recommended a preliminary parameter set of N = 3 and M = 5 (reference 2). These techniques should reduce the number of false alarms that naturally occur from random noise variation, and will provide good data sets for the track quality assessment.

3.4 TRACK QUALITY MEASURE

Knowing the existence of a moving vehicle is not all the information necessary to react to a potential target. We also have to know information about its relative direction and velocity to insure that proper and timely measures can be taken when required. Unfortunately, this latter information can vary greatly with signal-to-noise ratio and footprint size. At present, potential air vehicle detections (AVDs) are determined by the 3/5 ruler as far as TEAL RUBY and HI-CAMP experimentation is concerned. This criterion may or may not give the quality of response needed to take appropriate countermeasures when required. Thus, direction and magnitude of a target's velocity vector have to be assessed in a meaningful way, and processing speed must be minimized. With this in mind, the following is proposed as a measure of track quality. Normally, we will propose the simplest measure, that of velocity error. However, this does not take into account the computational complexity of estimate. In other words, an algorithm requiring 100 frames of data may provide a better estimate of the velocity vector, but may take such a long time to solve that it becomes an undesirable option for target detection. This implies that a better measure of track quality may be to normalize this error to the number of frames required for the estimation. Specifically, we define the track quality (TQ) as

$$TQ = [1.0 - \frac{||\underset{\sim}{V}_C - \underset{\sim}{V}_A||}{||\underset{\sim}{V}_A||}] \cdot \frac{5}{N_F} \tag{10}$$

with

$\underset{\sim}{V}_C \cong$ the calculated velocity

$\underset{\sim}{V}_A \cong$ the actual velocity

$N_F \cong$ the number of frames required for processing

The factor of 5 in this equation is the frame-normalizing factor based on the 3/5 rule requiring at least 5 frames will be used to create a track. Hence, an algorithm with perfect velocity estimations in five frames will have a TQ of 1.0.

4.0 SUMMARY

In this report we have recommended a number of figure-of-merit definitions which will be applied to stationary, slow- and fast-moving target detection algorithm performance assessments.

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